JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Study of $c\bar{c}c\bar{c}$ and $c\bar{c}s\bar{s}$ at Belle

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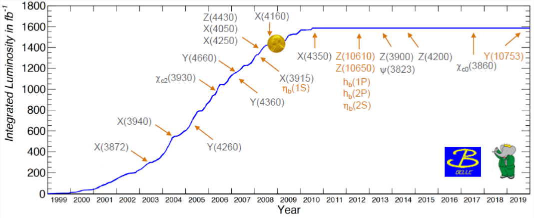
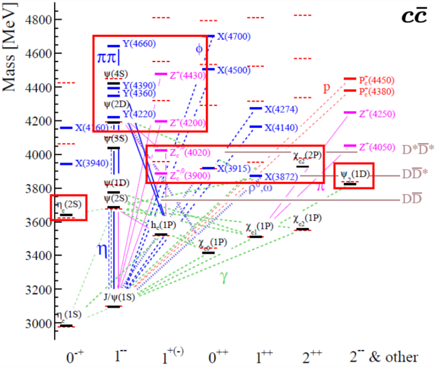
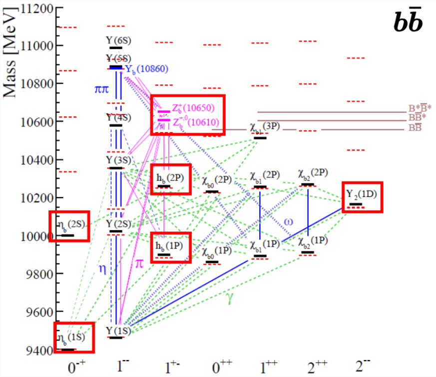
Quarkonium(-like) mess

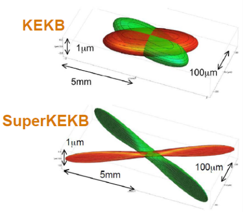
- Impressive legacy
- Below $D\bar{D}/B\bar{B}$ thresholds $c\bar{c}$ and $b\bar{b}$ match QCD;
- Many exotic states observed in the past decade are hard to fit these spectra.







From Belle to Belle II: experiment overview

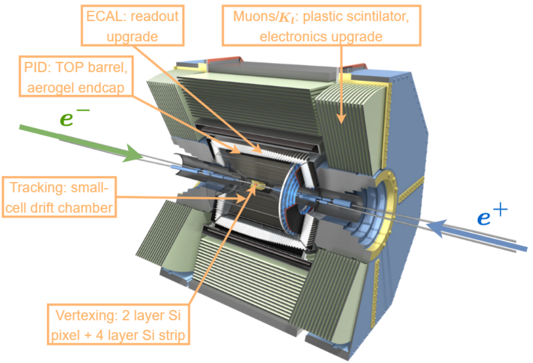


SuperKEKB:

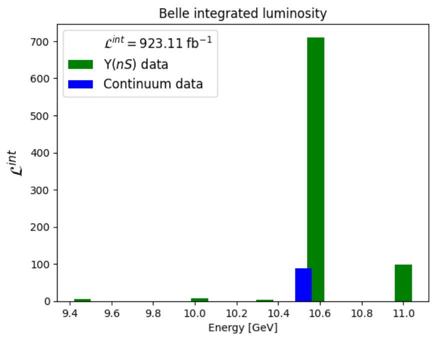
- Asymmetric e^+e^- collider at KEK (Tsukuba, Japan);
- Energy adjustment: 3.5/8.0 GeV (Belle) $\rightarrow$ 7.0/4.0 GeV (Belle II);
- "Nano-beams" $\times$ current increase (x2) = x40 inst. luminosity increase;

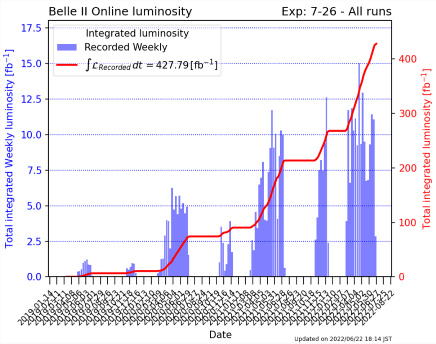
Belle II detector upgrade:

- Higher background:
  - Radiation damage;
  - Detector readout;
- Higher event rate ($\sim$ 30 kHz):
  - Trigger, DAQ, computing;
- Boost change:
  - Vertexing improvement;



What data samples are available today?





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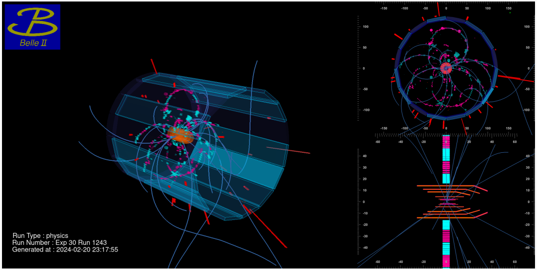
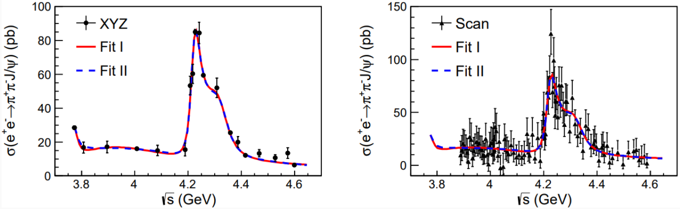
First recorded collisions of Run 2



The puzzle of $Y(4260)$

- A plethora of Y states ($J^{PC} = 1^{--}$) has been observed by B-factories while in parallel being extensively studied by theorists:
  - A $Y(4260)$ state with mass of $(4259 \pm 8^{+2}_{-6})$ MeV was observed in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ by BaBar (confirmed by Belle and CLEO);
    Phys. Rev. Lett. 95, 142001 (2005) Phys. Rev. D 74, 091104 (2006) Phys. Rev. Lett. 99, 182004 (2007)
  - Lattice QCD calculation predicts $Y(4230)$ predicts it to have a mass of (4238 ± 31) MeV by treating it as a molecule. It also predicts existence of two additional states: $cs\bar{c}\bar{s}$ around (4450 ± 100) MeV and $cc\bar{c}\bar{c}$ around (6400 ± 50) MeV.
    Phys. Rev. D 73, 094510 (2006)
  - BESIII study has shown that the s.c. $Y(4260)$ is not a simply a resonance, but two:
    - The $Y(4230)$ with the mass of $(4222.0 \pm 3.1 \pm 1.4)$ MeV and width of $(44.1 \pm 4.3 \pm 2.0)$ MeV Phys. Rev. Lett. 118, 092001 (2017) Phys. Rev. Lett. 118, 092002 (2017) Phys. C 38, 043001 (2014) Phys. Rev. D 99, 091103 (2019) Phys. Rev. Lett. 122, 102002 (2019)
    - The $Y(4360)$ with the mass of $(4320.0 \pm 10.4 \pm 7.0)$ MeV and width of $(101.4^{+25.3}_{-19.7} \pm 10.2)$ MeV



Phys. Rev. Lett. 118, 092001 (2017)

Introduction

- **BESIII:** observation of a structure with the mass of $(4487.7 \pm 13.3 \pm 24.1)$ MeV in the cross-section measurements of $e^+e^- \to K^+K^- J/\psi$ (matches $cs\bar{s}\bar{s}$ lattice QCD prediction);

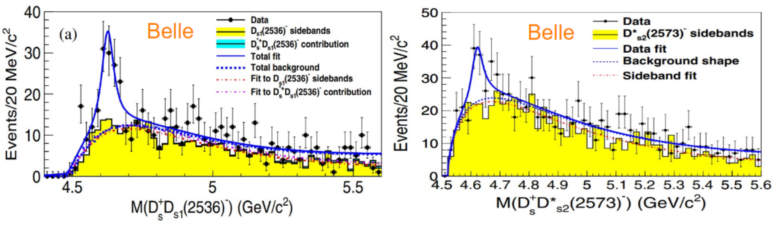
  Phys. Rev. D 97, 071101 (2018)

- **Belle:** observation of a structures with the masses of $(4625.9^{+6.2}_{-6.0} \pm 0.4)$ MeV and $(4619.8^{+8.9}_{-8.0} \pm 2.3)$ MeV in the cross-section measurements of $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ respectively

  Phys. Rev. D 100, no.11, 111103 (2019) Phys. Rev. D 101, no.9, 091101 (2020)

- **LHCb:** a narrow peak near the double-J/ψ threshold (dubbed $X(6900)$, also confirmed by ATLAS and CMS) - $[QQ][\bar{Q}\bar{Q}]$?

  Phys. Rev. Lett. 127, no.8, 082001 (2021) Rept. Prog. Phys. 86 (2023) no.2, 026201



Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

$J.High Energ.Phys. 2023, 121 (2023)$

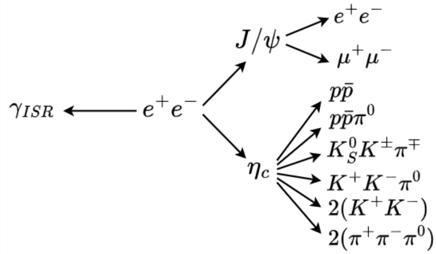
Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

Motivation: $\eta_c J/\psi$ is the lowest mass combination of charmonia that a vector $cc\bar{c}\bar{c}$ can decay into. Might have large BF.

Data: 980 fb^{-1} ($\Upsilon(nS)$ and continuum)

Strategy:

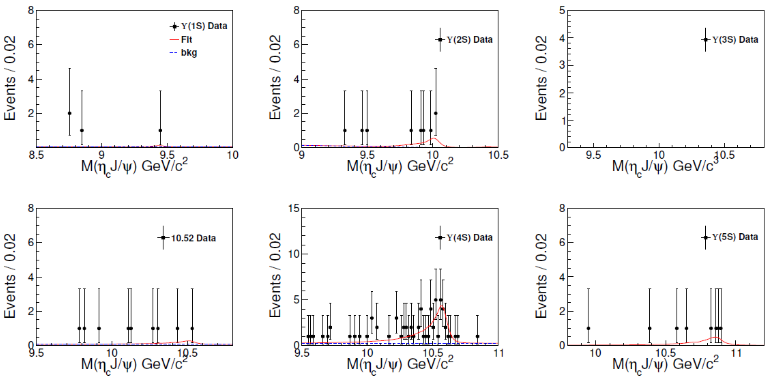
- ISR allows searching for $cc\bar{c}\bar{c}$ in the near-threshold region.
- Cross-section of $e^+e^- \to \eta_c J/\psi$ is first scanned on the $\Upsilon(nS)$ energy points:
  - analysis validation
  - NNLO nonrelativistic QCD approach check.
- Search for $\eta_c J/\psi$ and Y_{cc} is performed in the near-threshold region.
- Measured cross-sections are then extrapolated to the near-threshold region to the near-threshold region to check if potential signals are coming from continuum.



Exclusive reconstruction

Cross-section calculation:

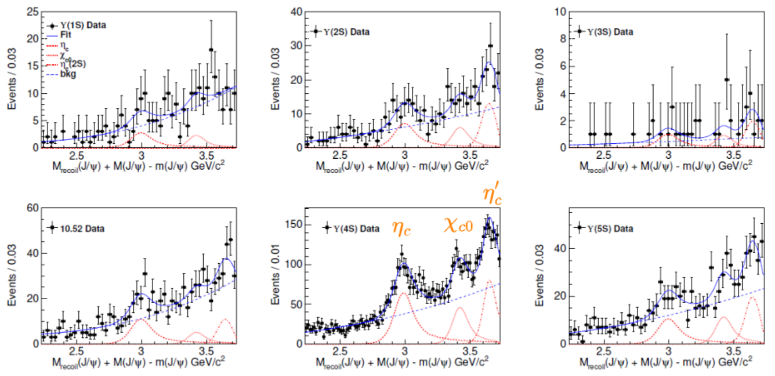
$$\sigma = \frac{N_{sig}}{\epsilon \mathcal{L} \mathcal{B}(J/\psi \to \ell^+\ell^-)\mathcal{B}(\eta_c \to 6 \text{ channels})} \quad (1)$$



Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

Inclusive reconstruction

- J/ψ recoil mass is studied: $M_{recoil}(J/\psi) \equiv \sqrt{|p_{e^+e^-} - p_{J/\psi}|^2}$
- $M_{recoil}(J/\psi) + M(J/\psi) - m(J/\psi)$ distribution is studied to achieve better resolution

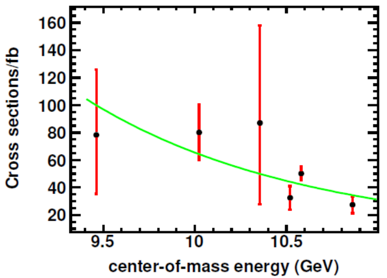


Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

Continuum production fractions for $e^+e^- \to \mu^+\mu^-$ are about 5/6 and 4.5/4.75 for $\Upsilon(1S)$ and $\Upsilon(2S)$ datasets, respectively. For the other $\Upsilon(nS)$ they are taken as 1.

Fit function:

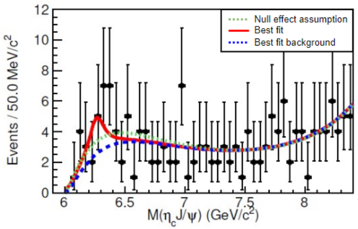
$$\sigma = A\frac{\sqrt{2\mu\Delta M}}{(\frac{s}{s_0})^n}$$

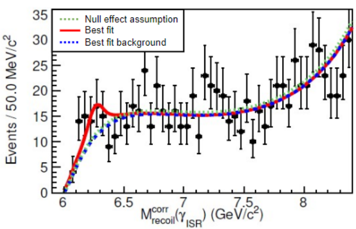


	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	10.52GeV	$\Upsilon(4S)$	$\Upsilon(5S)$
$\mathcal{L}[\mathrm{fb}^{-1}]$	5.7	24.9	2.9	89.4	711.0	121.4
N^{exc}	$0.7^{+1.5}_{-0.9}$	$6.2^{+3.1}_{-2.3}$	< 1.9	$2.6^{+3.5}_{-2.5}$	$45.0^{+8.9}_{-8.2}$	$6.5^{+3.4}_{-2.7}$
ϵ^{exc}	8.3%	6.9%	5.7%	5.6%	5.6%	5.4%
$\sigma^{\mathrm{exc}}[\mathrm{fb}]$	$57^{+122}_{-73} \pm 6$	$140^{+70}_{-52} \pm 14$	< 442	$20^{+27}_{-19} \pm 6$	$44^{+9}_{-8} \pm 5$	$39^{+20}_{-14} \pm 7$
N^{inc}	23.7 ± 12.3	62.0 ± 17.9	8.5 ± 5.2	94.7 ± 23.8	1116.2 ± 62.9	91.1 ± 21.5
ϵ^{inc}	38.6%	29.6%	26.4%	26.1%	25.4%	24.7%
σ^{inc} [fb]	$89.1^{\pm 46.2}_{\pm 20.5}$	$70.1^{\pm 20.2}_{\pm 8.9}$	$91.8^{\pm 56.2}_{\pm 52.3}$	$33.8^{\pm 8.5}_{\pm 2.8}$	$52.1^{\pm 2.9}_{\pm 5.0}$	$25.4^{\pm 6.0}_{\pm 2.8}$
σ^{comb} [fb]	$78.3^{+47.5}_{-43.0}$	80.2 ± 20.4	$87.0^{+71.0}_{-59.0}$	32.5 ± 8.5	50.2 ± 5.0	27.5 ± 6.1

$e^+e^- \to \eta_c J/\psi$ near threshold

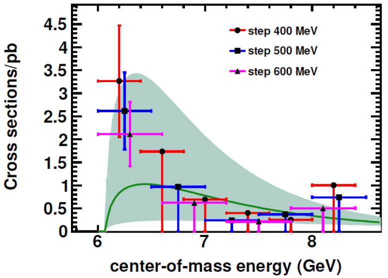
- Common events are removed from the inclusive reconstruction
- Signal count is 9 ± 4 and 23 ± 11 for exclusive and inclusive reconstructions
- The enhancement has a 2.1σ significance, located at (6267 ± 43) MeV mass and has a width of (121 ± 72) MeV)





Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

- The effective luminosity is calculated in each region
  Phys. Lett. B 241, 278 (1990)
- $\pm 1\sigma$ area of the cross-section lineshape extrapolation is consistent with the threshold enhancement.



regions $[\mathrm{GeV}/c^2]$	N_{prod} $\boxed{\times 10^2}$	$\sigma[\mathrm{pb}]$
$[6.0, 6.4]$	13.1 ± 3.6	$3.3 \pm 0.9 \pm 0.8$
$[6.4, 6.8]$	< 8.2	< 1.7
$[6.8, 7.2]$	< 3.9	< 0.7
$[7.2, 7.6]$	< 2.7	< 0.4
$[7.6, 8.0]$	< 2.1	< 0.3
$[8.0, 8.4]$	< 10.4	< 1.0
$[6.0, 6.5]$	13.4 ± 4.0	$2.7 \pm 0.8 \pm 0.2$
$[6.5, 7.0]$	< 6.1	< 1.0
$[7.0, 7.5]$	< 1.9	< 0.2
$[7.5, 8.0]$	< 3.8	< 0.4
$[8.0, 8.5]$	< 9.9	< 0.7
$[6.0, 6.6]$	13.3 ± 4.2	$2.1 \pm 0.7 \pm 0.2$
$[6.6, 7.2]$	< 5.0	< 0.6
$[7.2, 7.8]$	< 2.3	< 0.2
$[7.8, 8.4]$	< 7.4	< 0.5

Observation of charmed strange mesons pair production in $\Upsilon(2S)$ decays and in e^+e^- annihilation at 10.52 GeV

$Phys. Rev. D 108, 112015 (2023)$

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

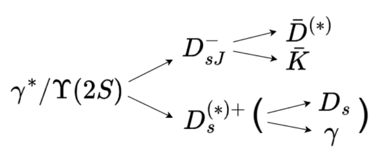
Motivation:

- Study of the "off-resonance" data allows excluding QCD component and study QED-ruled production standalone.

Background knowledge:

- $c\bar{c}$ constitutes about 40% of total hadronic production in continuum;
- Hadronic decays of $\Upsilon(nS)$ are OZI suppressed $\rightarrow$ study is scarce;
  - BaBar reports $\boldsymbol{\mathcal{B}[\Upsilon(1S) \rightarrow D^{*\pm} X] = (2.52 \pm 0.13 \pm 1.15)\%}$ at $(98.9 \pm 0.9) \times 10^6$ $\Upsilon(1S)$ events (Th: $\boldsymbol{\mathcal{B}[\Upsilon(1S) \rightarrow D^+ D^-] = 10^{-4} - 10^{-5}}$).
    Phys. Rev. D 81 (2010) 011102 Phys. Rev. D 74 (2006) 094016
  - Theoretical predictions:
    - Splitting of a virtual gluon Phys. Lett. B 77 (1978) 299
    - Annihilation into an octet state Phys. Rev. D 76 (2007) 051105
    - NP process with exotic couplings to heavy quarks Phys. Rev. D 81 (2010) 075017

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV



$^* D_{sJ}^{(*)} = D_{s1}(2536)$ or $D_{s2}^*(2573)$

Data:

- **24.7 fb^{-1}** at $\boldsymbol{\Upsilon(2S)}$ $\sim (158 \pm 4) \times 10^6$ events
- **89.5 fb^{-1}** at $\sqrt{s} = \mathbf{10.52}$ **GeV**

Analysis strategy:

- Full reconstruction of $D_s^{(*)}$
- D_s decays into $\phi(\to K^+K^-)\pi^+$, $K_S^0(\to \pi^+\pi^-)K^+$, $\bar{K}^*(892)^0(\to K^-\pi^+)K^+$, $\rho(\to \pi^+\pi^0)\phi$ $\eta\pi^+$ and $\eta'\pi^+$ are reconstructed.
- Partial reconstruction for the D_{sJ}^- final state:
  - The flavor is determined with the produced K
  - The remaining $\bar{D}^{(*)}$ is observed indirectly through its recoil against the $D_s^{(*)}$ - K system using the known kinematics.
- Simulated D_{sJ}^- decay modes: $K^-\bar{D}^0$, $K_S^0D^-$, $K^-\bar{D}^*(2007)^0$ and $K_S^0D^*(2010)^-$

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

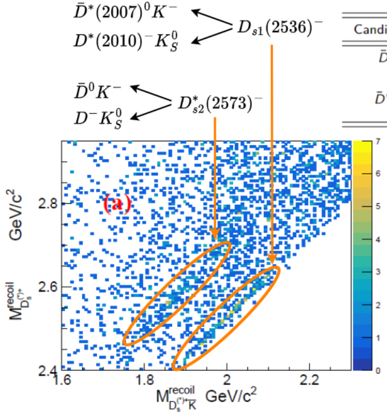
$\bar{D}^{(*)}$ is determined through the recoil of $D_s^{(*)+}\bar{K}$:

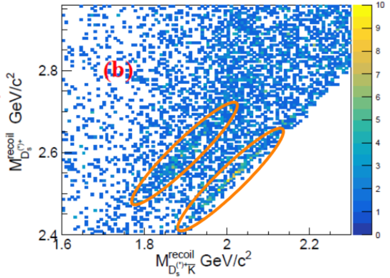
$$M_{\bar{D}^{(*)}} = M^{recoil}_{D_s^{(*)+}\bar{K}} \equiv \sqrt{(E_{c.m.} - E_{D_s^{(*)+}} - E_{\bar{K}})^2 - (\vec{p}_{c.m.} - \vec{p}_{D_s^{(*)+}} - \vec{p}_{\bar{K}})^2} \quad (2)$$

And isolate production of D_{sJ}^- in the $\bar{K}\bar{D}^{(*)}$ final state through recoil defined as:

$$M_{\bar{K}\bar{D}^{(*)}} = M^{recoil}_{D_s^{(*)+}} \equiv \sqrt{(E_{c.m.} - E_{D_s^{(*)+}})^2 - (\vec{p}_{c.m.} - \vec{p}_{D_s^{(*)+}})^2} \quad (3)$$

Candidate	Resolution [MeV]	Criteria
$\bar{D}$	≈ 50 MeV	$\lvert M^{recoil}_{D_s^{(*)}+\bar{K}} - m_{\bar{D}}\rvert < 150$ MeV
$\bar{D}^*$	31.8 ± 0.3 MeV (34%) 74.2 ± 1.0 MeV (66%)	$\lvert M^{recoil}_{D_s^{(*)}+\bar{K}} - m_{\bar{D}^*}\rvert < 200$ MeV





Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

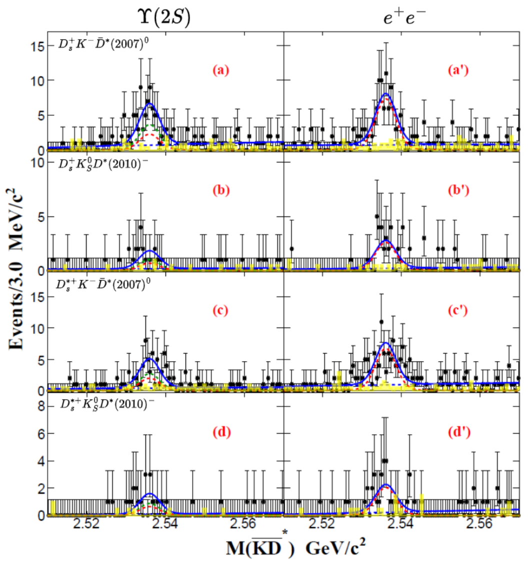
Large mass resolutions (due to the common variables in Eq. 2 and Eq. 3) can be cured by substituting Eq. 3 with:

$$M_{\bar{K}\bar{D}^{(*)}} = M^{recoil}_{D_s^{(*)+}} - M^{recoil}_{D_s^{(*)+}\bar{K}} + m_{\bar{D}^{(*)}} \tag{4}$$

$\boldsymbol{N^{sig}_{\Upsilon(2S)}}$ and $\boldsymbol{N^{sig}_{cont}}$ for DsJ^- are estimated by fitting $M_{\bar{K}\bar{D}^{(*)}}$ distributions simultaneously with the common ratios $\mathcal{B}(D^-_{sJ} \to K^0_S D^{(*)-})/(D^-_{sJ} \to K^- D^{(*)0})$ between the final states.

Fit function:

$$PDF = N_1 \cdot G(\mu^{PDG}_{D^-_{sJ}}, 2.4/6.5\,\text{MeV}) + N_2 \cdot BW(\mu^{PDG}_{D^-_{sJ}}, \sigma^{PDG}_{D^-_{sJ}}) \tag{5}$$



Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

The yield acquired on $\Upsilon(2S)$ can be interpreted as:

$$N^{sig}_{tot} = N^{sig}_{\Upsilon(2S)} + N^{sig}_{cont} \times \frac{\mathcal{L}_{\Upsilon(2S)} \cdot s_{cont}}{\mathcal{L}_{conr} \cdot s_{\Upsilon(2S)}} \tag{6}$$

Branching fractions and Born cross-sections calculation:

$$\begin{aligned}
\mathcal{B}\left(\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-\right) \mathcal{B}\left(D_{sJ}^- \to \bar{K}\bar{D}^{(*)}\right) &= \frac{N^{\mathrm{sig}}_{\Upsilon(2S)} - f_{\mathrm{scale}} \cdot N^{\mathrm{sig}}_{\mathrm{cont}}}{N_{\Upsilon(2S)} \times \sum \varepsilon_i \mathcal{B}_i} \\
\sigma^{\mathrm{B}}\left(e^+e^- \to D_s^{(*)+} D_{sJ}^-\right) \mathcal{B}\left(D_{sJ}^- \to \bar{K}\bar{D}^{(*)}\right) &= \frac{N^{\mathrm{sig}}_{\mathrm{cont}} \times |1-\Pi|^2}{\mathcal{L}_{\mathrm{cont}} \times \sum \varepsilon_i \mathcal{B}_i \times (1+\delta_{\mathrm{ISR}})}
\end{aligned} \tag{7}$$

Final state (f)	$N^{K^-}_{\Upsilon(2S)}$	$\mathcal{B}^f_{\Upsilon(2S)f}\,\mathcal{B}^{K^-\bar{D}^{(*)0}}_{D^-_{sJ}}$ $\left(\times 10^{-5}\right)$	$S^{\Upsilon(2S)}$
$D_s^+ D_{s1}(2536)^-$	$43 \pm 9 \pm 2$	$1.4 \pm 0.3 \pm 0.1$	5.3
$D_s^{*+} D_{s1}(2536)^-$	$31 \pm 8 \pm 2$	$2.0 \pm 0.5 \pm 0.1$	4.3
$D_s^+ D_{s2}^*(2573)^-$	$51 \pm 15 \pm 5$	$1.6 \pm 0.5 \pm 0.1$	3.8
$D_s^{*+} D_{s2}^*(2573)^-$	$20 \pm 12 \pm 2$	$1.3 \pm 0.8 \pm 0.1$	1.6
Final state (f)	$N^{K^-}_{cont}$	$\sigma^{\mathrm{Born}}\mathcal{B}^{K^-\bar{D}^{(*)0}}_{D^-_{sJ}}$ (fb)	S^{cont}
$D_s^+ D_{s1}(2536)^-$	$86 \pm 10 \pm 2$	$58 \pm 7 \pm 1$	13.9
$D_s^{*+} D_{s1}(2536)^-$	$79 \pm 10 \pm 2$	$101 \pm 13 \pm 2$	11.8
$D_s^+ D_{s2}^*(2573)^-$	$102 \pm 17 \pm 21$	$67 \pm 11 \pm 14$	7.1
$D_s^{*+} D_{s2}^*(2573)^-$	$102 \pm 16 \pm 6$	$126 \pm 20 \pm 7$	7.6

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

Curious takeaways:

1. The strong decay is expected to dominate in $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-$ process:

   $$R_1 \equiv \mathcal{B}(\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-)/\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-)$$

   $$R_2 \equiv \sigma^{Born}(e^+e^- \to D_s^{(*)+} D_{sJ}^-)/\sigma^{Born}(e^+e^- \to \mu^+\mu^-)$$

   $R_1/R_2 = 9.8 \pm 2.5,\ 8.0 \pm 2.4,\ 9.7 \pm 3.0$ and 4.4 ± 2.8

   (for $D_s^+ D_{s1}(2536)^-,\ D_s^{*+} D_{s1}(2536)^-,\ D_s^+ D_{s2}^*(2573)^-$ and $D_s^+ D_{s2}^*(2573)^-$)

2. The ratios

   $$\frac{\mathcal{B}(D_{s1}(2536)^- \to K_S^0 D^*(2010)^-)}{\mathcal{B}(D_{s1}(2536)^- \to K^- D^*(2007)^0)} = 0.59 \pm 0.08 \pm 0.02$$

   $$\frac{\mathcal{B}(D_{s2}^*(2573)^- \to K_S^0 D^-)}{\mathcal{B}(D_{s2}^*(2573)^- \to K^- D^0)} = 0.64 \pm 0.12 \pm 0.04$$

   are in good agreement with the expectation from isospin symmetry (with K_S^0 only half of the neutral kaons can be reconstructed).

Study of $e^+e^- \to D_s^+ D_{s0}^*(2317)^- A$ + c.c. and $e^+e^- \to D_s^+ D_{s1}(2460)^- A$ + c.c at Belle

PRELIMINARY

Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

Invariant mass system	Decay from:	Range [GeV/c^2]
$D_s^- D_s^+$	B_s^0	[3.936 - 5.298]
$D_s^- D_s^+ \pi^0$	B_s^0	[4.071 - 5.433]
$D_s^- D_s^{*+}$	B_s^0	[4.080 - 5.433]
$D_s^- D_{s0}^*(2317)^+$	B_s^0	[4.285 - 5.433]
$J/\psi\phi$	B^0	[4.117 - 4.783]
$J/\psi\phi$	$B^\pm$	[4.117 - 4.783]
$J/\psi\phi$	continuum	all range
$D_s^- D_{s0}^*(2317)^+$, $D_s^- D_{s1}(2460)^+$, $D_s^- D_s^+ \pi^0$, $D_s^- D_s^{*+}$	continuum	all range

$B_s^0 \to D_s^{(*)+} D_s^{(*)-} \pi^0$

$B^{0,\pm} \to J/\Psi\phi K^{0,\pm}$

$e^+e^- \to J/\Psi\phi$ + anything

$e^+e^- \to D_s^{(*)+} D_s^{(*)-}$ + anything

$X(4274)$
$X(4685)$

$X(4630)$
$X(4500)$
$X(4700)$

LHCb results:

- 9 fb^{-1} of data
- 7 neutral X states
- 3 charged Z states

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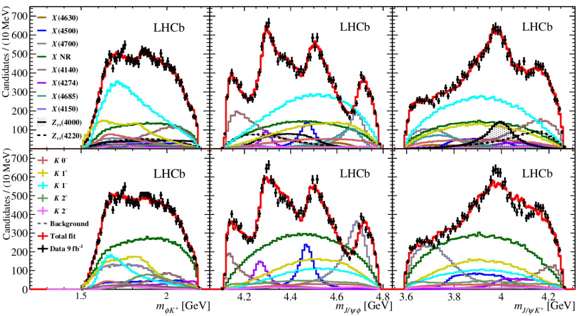


Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

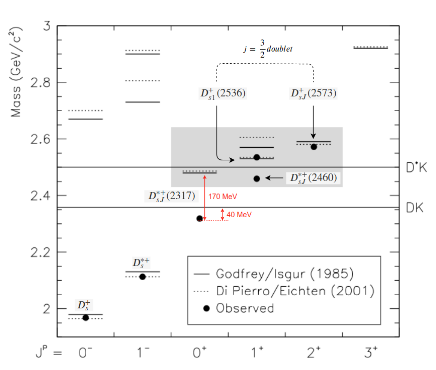
First $e^+e^- \to D_s \pi^0 X$ process studies:

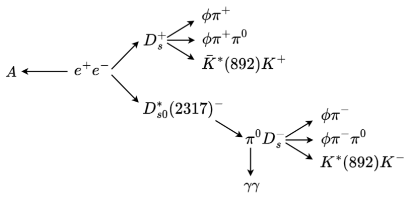
- BaBar: 1267 yield on 91 fb^{-1}
- Belle: 761 yield on 87 fb^{-1}

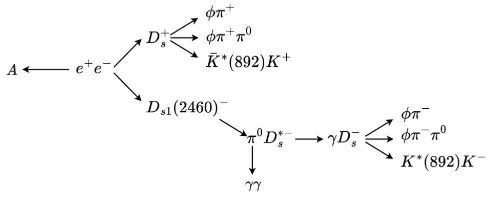
Extrapolation from the old analysis with $D_s^*(2317)$ only, but to the whole data set:

- **Belle @$\Upsilon(4S)$**: 6226   Only $D_s^*(2317)$!

With one extra D_s (e.g. +3 charged tracks), efficiency is expected to drop (< 1%). Around 100 events are expected on full Belle dataset.







Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

Signal MC

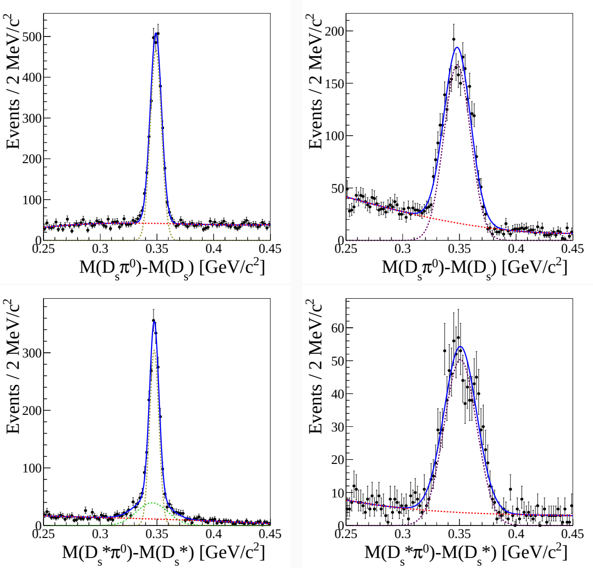
The following peaking contributions are expected

$D_{sJ}(2317)^+$ invariant mass region:

- True $D_{sJ}(2317)^+$ peak
  $\sigma = (4.76 \pm 0.8)$ MeV
- $D_{sJ}(2460)^+$ reflection peak
  $\sigma = (11.8 \pm 0.3)$ MeV

$D_{sJ}(2460)^+$ invariant mass region:

- True $D_{sJ}(2460)^+$ peak
  $\sigma = (5.07 \pm 0.13)$ MeV
- $D_{sJ}(2317)^+$ reflection peak
  $\sigma = (14.6 \pm 0.7)$ MeV
- $D_{sJ}(2460)^+$ "broken signal"
  $\sigma = (16.9 \pm 1.8)$ MeV



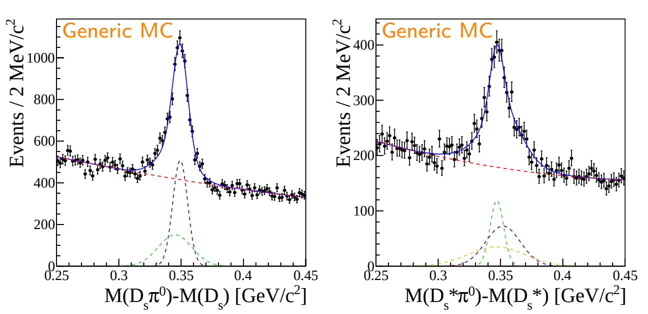
Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

$$\Delta M(D_s\pi^0) = N_1 G(\mu_1,\sigma_1) + f^{down} N_2 G(\mu^{down},\sigma^{down})$$
$$\Delta M(D_s^*\pi^0) = N_2 G(\mu_2,\sigma_2) + f^{up} N_1 G(\mu^{up},\sigma^{up}) + f^{broken} N_2 G(\mu^{broken},\sigma^{broken}) \quad (8)$$

ref: N $= 3{,}843 \pm 67$, $\mu = 348.9 \pm 0.1$, $\sigma = 6.20 \pm 0.10$

ref: N $= 835 \pm 31$, $\mu = 347.1 \pm 0.2$, $\sigma = 5.80 \pm 0.20$

Topology type	μ, [MeV]	σ, [MeV]	N
True $D_{s0}^*(2317)$ signal	349.3 ± 0.2	5.97 ± 0.25	$3{,}797 \pm 137$
Feed-down background	345.1 (fixed)	13.5 (fixed)	$0.3297 \cdot N_2$
True $D_{s1}(2460)$ signal	347.1 ± 0.5	5.46 ± 0.60	811 ± 155
Feed-up background	352.0 (fixed)	13.9 (fixed)	$3.042 \cdot N_1$
$D_{s1}(2460)$	346.7 (fixed)	22.7 (fixed)	$1.189 \cdot N_2$

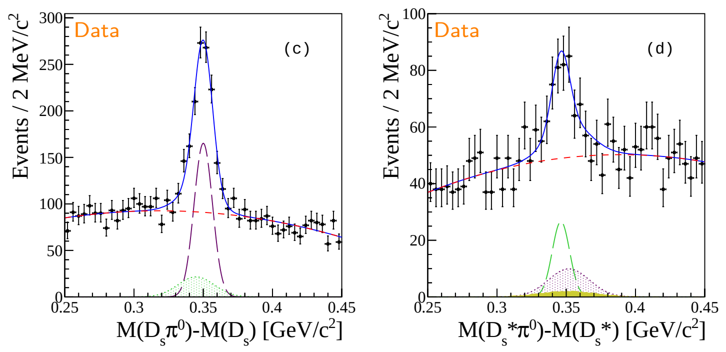


Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

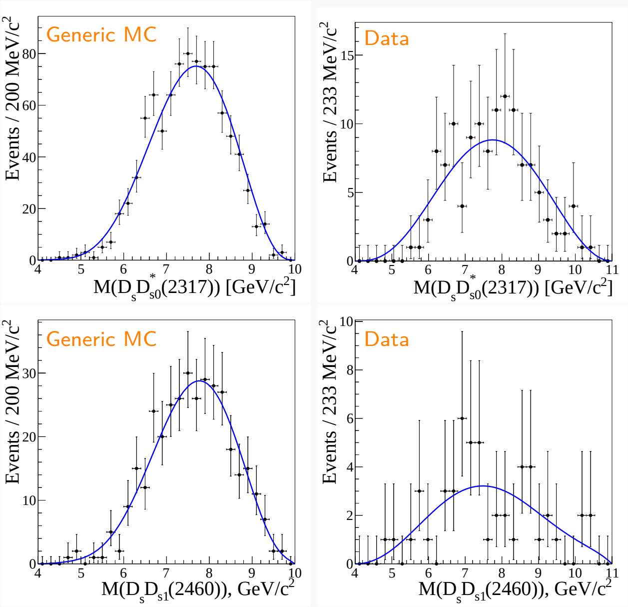
Cut-based selection → MVA selection

Topology type	μ, [MeV]	σ, [MeV]	N
True $D_{s0}^*(2317)$	350.0 ± 0.5	6.64 ± 0.53	688 ± 62
Feed-down bkg.	344.8 (fixed)	13.1 (fixed)	$1.688 \cdot N_2$
True $D_{s1}(2460)$	346.2 ± 1.7	6.27 ± 1.55	105 ± 27
Feed-up bkg.	351.9 (fixed)	14.8 (fixed)	$0.134 \cdot N_1$
Broken signal	351.0 (fixed)	20.4 (fixed)	$0.247 \cdot N_2$

Cuts: $N(D_{s0}^*(2317)) = 370 \pm 45$ $\quad N(D_{s1}(2460)) = 68 \pm 22$



Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle



Study of $e^+e^- \to D_s^+ D_{sJ}^- A$ + c.c. at Belle

$$\frac{Br(D_{s1}(2460) \to D_s^* \pi^0)}{Br(D_{s0}^*(2317) \to D_s \pi^0)} \times \frac{\sigma(D_{s1}(2460), \text{MVA})}{\sigma(D_{s0}^*(2317), \text{MVA})} = 0.26 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$$

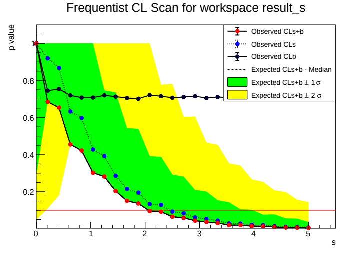
*The value earlier measured by Belle is $0.29 \pm 0.06 \pm 0.03$

**The value predicted by theory is 3

$$\sigma(e^+e^- \to D_s^+ D_{sJ}^{(*)-} A)\mathcal{B}(D_s^- \to 3 \text{ modes})\mathcal{B}(D_s^+ \to 3 \text{ modes}) = \frac{N^{UL} \times |1-\Pi|^2}{\mathcal{L} \times \Sigma_{ij} \varepsilon_{ij}^* \mathcal{B}_i \mathcal{B}_j \times (1+\delta)_{ISR}}$$

Curious takeaways:

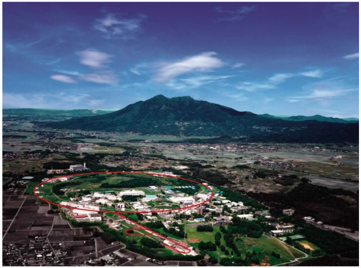
- The estimated ratio of branching fractions is consistent with earlier Belle study.
- $D_s D_{sJ}$ invariant mass distributions on data appeared to be PHSP-distributed.
- Cross-section UL for the accessible X states are evaluated.



Decay chain	Total error [%]	Estimated N_{90}^{UL}	$\sigma^{UL} \times \mathcal{B}(X \to D_s D_{sJ}^*)$ [fb^{-1}]
$e^+e^- \to X(4274)A$	13.3	2.45	122.5
$e^+e^- \to X(4685)A$	14.1	2.04	101.8
$e^+e^- \to X(4630)A$	18.3	2.05	228.1
$e^+e^- \to X(4500)A$	18.0	2.34	260.1
$e^+e^- \to X(4700)A$	18.7	2.18	241.8

Summary

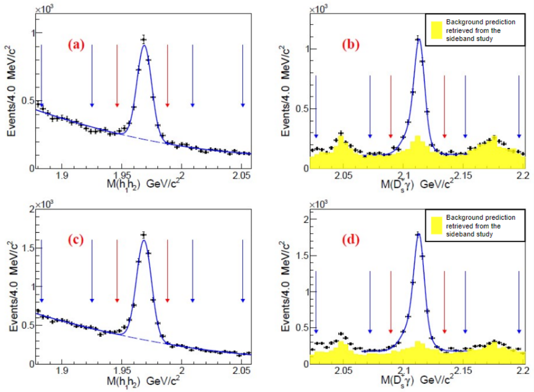
1. No significant signal is seen in the $e^+e^- \to \eta_c J/\psi$ process near threshold. The observed enhancement can be explained by continuum contribution.
2. Born cross-sections and branching fractions are measured for the $e^+e^-/\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-$ processes. This allows to conclude about the intrinsic features of $\Upsilon(2S)$ decays.
3. No significant signal is seen in the $D_s D_{sJ}^{(*)}$ system. Upper limits on the accessible X states that were earlier reported by LHCb are set.



Backup

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

- Cut-based selection is developed for the $D_s^{(*)-}$ candidates;
- D_s^- invariant mass fit:
$$\sigma_{D_s^-} = 7.0 \pm 0.1 \text{ MeV}$$
- BCS applied on D_s^{*-} candidates leads to peaking background (studied in a side-band).
Fit performed:
$$\sigma_{D_s^{*-}} = 6.7 \pm 0.4 \text{ MeV}$$



Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

- $M^2_{recoil} = |p_{e^+e^-} - p(\eta_c) - p(J/\psi)|^2$;
- At least four charged tracks are required in the inclusive reconstruction to suppress QED background;

Candidate	Criteria
All tracks	$dr < 1.0$ cm
	$\|dz\| < 4$ cm
	$p_T > 100$ MeV
K	$\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$
p	$\mathcal{L}_p/(\mathcal{L}_p + \mathcal{L}_\pi) > 0.6$
	$\mathcal{L}_p/(\mathcal{L}_p + \mathcal{L}_K) > 0.6$
μ	$\mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_p + \mathcal{L}_K) > 0.6$
e	$\mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_{non-e}) > 0.01$
γ_{ISR}	$E_\gamma > 1$ GeV
K^0_S	NN
π^0	$E_\gamma > 25$ MeV (barel)
	$E_\gamma > 50$ MeV (endcap)
	$155 < M_{\gamma\gamma} < 155$ MeV
γ^{BS}	50 mrad cone
J/ψ	$3 < M(e^+e^-) < 3.12$ GeV
	$3.075 < M(\mu^+\mu^-) < 3.125$ GeV
η_c	$2.78 < M(\eta_c) < 3.08$ GeV
BCS	$\min(M^{recoil}_{\eta_c J/\psi})$

Observation of $c\bar{s} + \bar{c}s$ in $\Upsilon(2S)$ decays and at 10.52 GeV

Candidate	Resolution [MeV]	Criteria
Tracks	-	$dr < 1.5$ cm $\|dz\| < 5$ cm $p_T > 0.1$ GeV $\mathcal{L}_K > 0.6$ $\mathcal{L}_\pi > 0.4$
K_S^0	$\approx$5	$\|M_{\pi^+\pi^-} - m_{K_S^0}\| < 3\sigma$ NN
ϕ	$\approx$3.3	$\|M_{K+K-} - m_\phi\| < 3\sigma$
$K^*(892)$	$<< 47.3$	$\|M_{K-\pi+} - m_{K^*(892)}\| < 105$ MeV
ρ^+	$<< 150$	$\|M_{\pi^+\pi^0} - m_\rho\| < 200$ MeV
π^0	$\approx$5	$\|M_{\gamma\gamma} - m_{\pi^0}\| < 3\sigma$ MeV
γ	-	$E_\gamma > 25$ MeV (barel) $E_\gamma > 50$ MeV (endcap)
η	$\approx$4 ($\rightarrow \pi^+\pi^-\pi^0$) $\approx$13.4 ($\rightarrow \gamma\gamma$)	$\|M_{\pi^+\pi^-\pi^0} - m_\eta\| < 3\sigma$ $\|M_{\gamma\gamma} - m_\eta\| < 3\sigma$ $E_\gamma > 100$ MeV
η'	$\approx$5	$\|M_{\eta\pi^+\pi^-} - m_{\eta'}\| < 3\sigma$
D_s	7.9 ± 0.1	$\|M_{h_1 h_2} - m_{D_s}\| < 3\sigma$
D_s^*	6.7 ± 0.4	$\|M_{\gamma D_s} - m_{D_s^*}\| < 50$ MeV $E_\gamma > 50$ MeV (barel) $E_\gamma > 100$ MeV (endcap) BCS: $\min(\chi^2)$

Signal MC. Optimized selection and BCS implementation.

In addition to the selection summarized on the right, the BCS selection was applied in the latest iteration of a study.

Selection optimization study has been conducted.

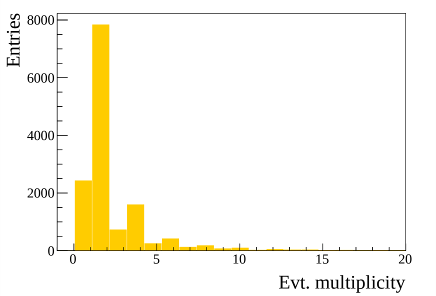


Figure 1: Signal MC. Event multiplicity before BCS application.

Particle	Selection criterion
Tracks	$dr < 0.5$ cm $dz < 3$ cm $P_{K_1}(K/\pi) > 0.5$ $P_{K_2}(K/\pi) > 0.2$ $P_{\pi}(K/\pi) < 0.9$
π^0	$E(\gamma) > 100$ MeV $p(\gamma\gamma) > 150$ MeV/c $\chi^2(\gamma\gamma) < 200$ $122 < M(\gamma\gamma) < 148$ MeV/c^2 $P_{\chi^2}(\gamma\gamma) > 1\%$
ϕ	$1.010 < M(KK) < 1.030$ GeV/c^2 $P_{\chi^2}(KK) > 0.1\%$
$K^*(892)$	$842 < M(K\pi) < 942$ MeV/c^2 $P_{\chi^2}(K\pi) > 0.1\%$
D_s	$1.9585 < M(D_s) < 1.9785$ GeV/c^2 $P_{\chi^2}(D_s) > 0.1\%$
$D_{s0}^*(2317)$	$p^*(D_s\pi^0) > 2.79$ GeV/c $P_{\chi^2}(D_s\pi^0) > 0.1\%$
Other	$\lvert cos\theta_H \rvert > 0.42$

Table 1: The summarized selection for $D_{s1}(2460)$ reconstruction.
* γ_* denotes the photon combined with D_s to create D_s^* candidate decaying into $D_s\gamma$.

Signal MC. $D_s D_{s0}^*(2317)$ system study (threshold case).

$$\varepsilon = 0.22 \pm 0.02\%$$

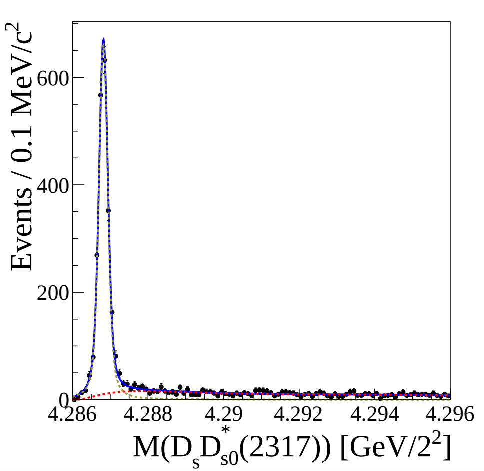


Figure 2: The $D_s D_{s0}^*(2317)$ invariant mass distribution in threshold case. The signal contribution is fitted by Voigt function, non-resonant background as approximated by the Threshold function.

MVA methods comparison

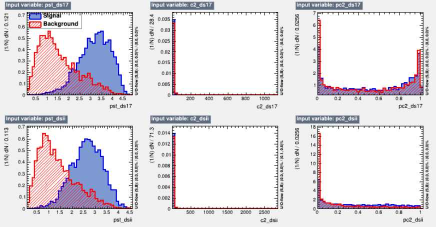


Figure 3: MVA input variables for signal (blue) and background (red) events.

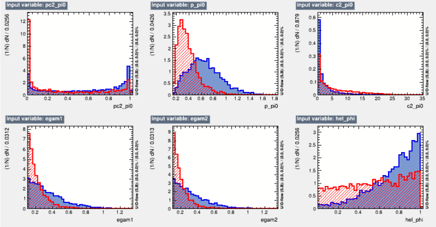


Figure 4: MVA input variables for signal (blue) and background (red) events.

- Pre-selection is applied.
- Performances of MLP, BDT, Fisher and DNN methods are compared → **MLP is chosen**
- Set of input variables is optimized with respect to correlation matrix → **redundant variables eliminated**.

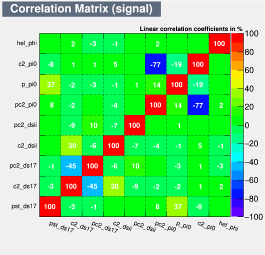


Figure 5: Input parameters Correlation Matrix for signal events.

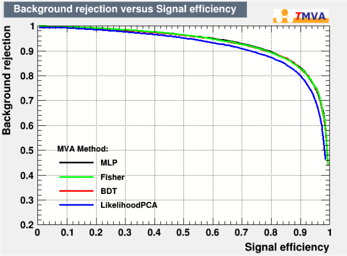


Figure 6: ROC curve.

MLP application

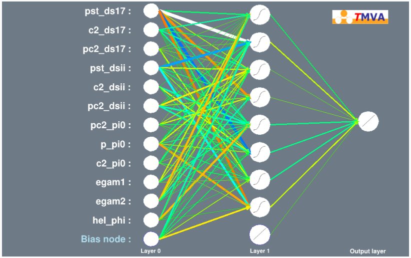


Figure 7: MLP architecture.

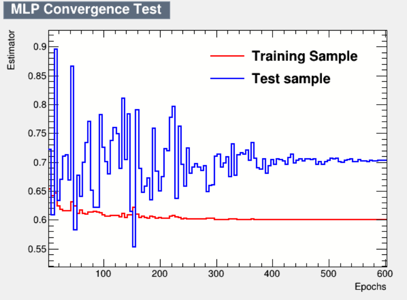


Figure 9: MLP convergence test.

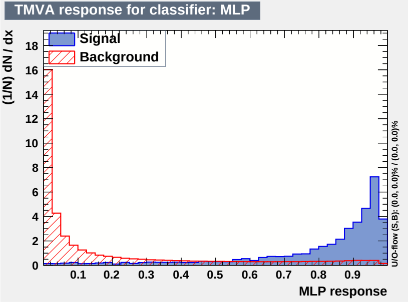


Figure 8: MLP response for classifier on training sample.

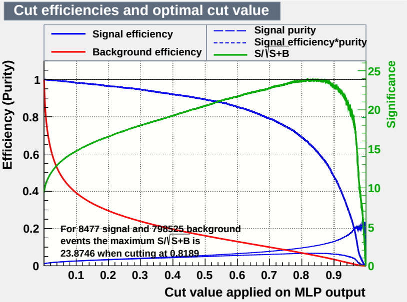


Figure 10: FoM dependence on classifier cut value.

Systematic uncertainties

Systematic Contribution	$D_s D_{s0}^*(2317)$ %	$D_s D_{s1}(2460)$ %
Charged tracks identification	3.21	3.21
Track reconstruction	2.10	2.10
MC statistics	1.82	2.42
Integrated luminosity	1.40	1.40
π^0 reconstruction	2.00	2.00
γ reconstruction	-	2.30
Secondary BF	5.83	5.62
Background fit PDF order	1.03	1.23
Mass cuts on secondary particles	5.58	7.80
TOTAL	9.50	11.22

Asymptotic method

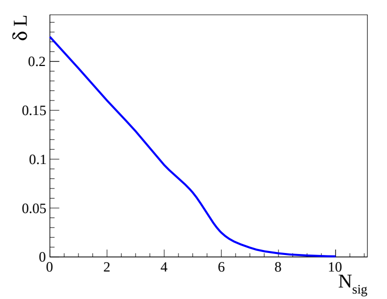
Equation to solve:

$$\frac{\int_0^{N^{90\%}} \mathcal{L}(x)dx}{\int_0^{+\infty} \mathcal{L}(x)dx} = 0.9 \qquad (9)$$

$N^{90\%}$ - wanted UL on the number of signal events.

Target dependency to study:

$$\Delta L = e^{\mathcal{L}(N_{sig}) - \mathcal{L}_0} \qquad (10)$$



Consideration of the systematic uncertainties:

$$\Delta(\Delta L) = \frac{\Delta\mathcal{L}_j \cdot \mathcal{L}_j}{\sqrt{2\pi\varepsilon_{syst} N_j^{sig}}} \cdot e^{-\frac{1}{2}\left(\frac{\Delta N_j^{sig}}{\varepsilon_{syst} N_j^{sig}}\right)^2} \qquad (11)$$

Cross-section UL calculation:

$$\sigma^{90\%} = \frac{N^{90\%}}{\varepsilon^{tot} \cdot \mathcal{L}^{int}} \qquad (12)$$

CL method

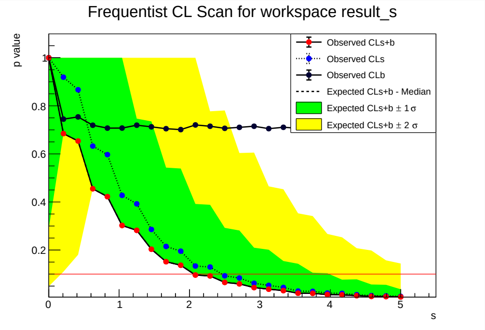
Likelihood ratio:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}|n_1, \ldots, n_{N_b})}{\mathcal{L}(\mu, \hat{\theta}|n_1, \ldots, n_{N_b})}, \qquad (13)$$

where $(\mu, \hat{\theta})$ are the parameters that maximize the likelihood for the set of observations $n_1, \ldots, n_{N_b}$; and $\hat{\hat{\theta}}$ maximizes the likelihood for a given value of μ.

Test statistics q_μ:

$$q_\mu = \begin{cases} -2ln\lambda(\mu) & \text{if } \mu > \hat{\mu}, \\ 0 & \text{otherwise} \end{cases} \qquad (14)$$



The level of agreement between the data and the hypothesized value of μ is quantified with the p-value:

$$p_{s+b} = P(q_\mu > q_{\mu,\text{obs}}|\mu) = \int_{\mu,\text{obs}}^{\infty} p(q_\mu|\mu)\text{d}q_\mu, \qquad (15)$$

where $> q_{\mu,\text{obs}}$ is the observed value of q_μ, and $p(q_\mu|\mu)$ denotes the probability density function of q_μ under the assumption of a signal strength of μ.

UL on μ at 90% CL is the largest value of μ such as p_{s+b} stays above 0.1